Quantifying uncertainties influencing the long-term impacts of oil prices on energy markets and carbon emissions

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Abstract

Oil prices have fluctuated remarkably in recent years. Previous studies have analyzed the impacts of future oil prices on the energy system and greenhouse gas emissions, but none have quantitatively assessed how the broader, energy system-wide impacts of diverging oil price futures depend on a suite of critical uncertainties. Here we use the MESSAGE integrated assessment model to study several factors potentially influencing this interaction, thereby shedding light on which future unknowns hold the most importance. We find that sustained low or high oil prices could have a major impact on the global energy system over the next several decades; and depending on how the fuel substitution dynamics play out, the carbon dioxide consequences could be significant (e.g., between 5% and 20% of the budget for staying below the internationally-agreed 2 °C target). Whether or not oil and gas prices decouple going forward is found to be the biggest uncertainty.

Introduction

Oil prices took a dramatic plunge starting in late-2014 and have remained low ever since. Combined with parallel developments in natural gas supply, this plunge has prompted questions regarding what the "new normal" might mean for global markets. How will falling oil and gas prices affect energy decision-making over the long term? Will they damage the business case for renewables? Will they stymie incentives to invest in energy efficiency? How do they change the outlook for coal and nuclear? Does this spell bad news for efforts to mitigate climate change? The International Energy Agency (IEA) recently found that, between now and 2040, lower oil prices will lead to marginally greater oil and gas demand and incrementally smaller renewables and coal demand, which on balance means slightly higher carbon dioxide (CO_2) emissions[1]. It is not unlikely that the energy and emissions impacts could be larger than this, however. What is more, the broader, energy system-wide impacts of diverging oil price futures are likely to depend on a number of key uncertainties.

Here we present work that unpicks several potentially influential factors, thereby going beyond economic analyses focusing on the very near term impacts of oil prices[2-6] and the limited number of scenario analyses for the mid-to-long term[1,7-10]. Using the MESSAGE integrated assessment model, we develop and analyze scenarios with wide-ranging oil price levels that are in line with recent market fluctuations. We then employ a suite of sensitivity analyses focusing on numerous climate policy, energy resource, and supply and demand technology uncertainties to explore which future unknowns hold the most importance for the global energy system and its resulting emissions. We find that sustained low or high oil prices could have a major impact on the former over the next several decades; and depending on how the fuel substitution dynamics play out, the CO_2 consequences could be significant (e.g., as little as 5% or as much as 20% of the cumulative emissions allowable for keeping global temperatures under the 2 °C threshold). By comparison, our calculated shifts are one to two orders of magnitude larger than those estimated by the IEA. That the *net* CO_2 emissions differences we find are not larger (or smaller) when oil prices either rise or fall is because of (i) parallel responses seen for carbon-intensive coal and low-carbon biomass (i.e., their benefits/consequences partially cancel out), and (ii) price-induced energy service demand responses across the end-use sectors (industry, transport, and buildings). Thus, if the goal is to mitigate carbon substantially, high oil prices offer no substitute for climate policies. Whether or not oil and gas prices decouple going forward is found to be the biggest uncertainty influencing the system-wide effects exhibited by our scenarios. The impacts also strongly depend on uncertainties surrounding the future potential of sustainable bioenergy supplies and the costs and availability/scalability of electric vehicles. In short, the energy and CO_2 impacts of diverging oil price futures depend not just on prices alone, but rather on a number of uncertain resource-, technology-, and policy-related factors.

Confronting uncertainties in oil prices and related factors

Given the importance of crude oil and natural gas in today's energy system, the prices of these two fossil resources – both their current levels and future expectations – are determining factors in technology and fuel choice decisions throughout the economy (e.g., transport, petro-chemicals, manufacturing, power generation, and building heating and cooling, among others). Oil and gas and their alternatives (namely coal, biomass, nuclear, solar, wind and other renewables) each generate a certain quantity of greenhouse gas emissions when produced, transported and converted to other energy forms. Hence, the (often inter-linked) prices of oil and gas are also important determinants of emissions. A suitable method for exploring the net energy and emissions impacts of oil and gas price developments is through scenario analysis aided by internally-consistent, systems-analytical tools with a long-term time horizon.[11]

Using one such tool, the MESSAGE integrated assessment modeling (IAM) framework (refs. [12,13]; see Methods and Supplementary Methods for further details), we modeled scenarios wherein global oil prices are sustained at either low (40-55 US$/bbl) or high (110-120 US$/bbl) levels over the next several decades to 2050. MESSAGE represents international markets for oil, gas and all other energy commodities/sectors; importantly, energy prices are calculated endogenously within this internally-consistent, general equilibrium framework. The two price thresholds we choose are consistent with the lower and upper ranges, respectively, seen for oil prices in recent years (monthly averages, not shown; after adjusting historical prices to US$2005)[14]. Figure 1 presents the oil price paths in the two diverging cases. These paths are meant to be stylized (they are not predictions); indeed, if the future is anything like the past, then oil price behavior will be somewhat more chaotic (over weekly/monthly intervals) than the sustained low/high levels depicted here. Prices could rise above or fall below these levels, or they could bounce around in between. With so many variables affecting the market price of crude oil[15] – and therefore so much uncertainty surrounding what those future prices will be – the explicit focus here is on the broader, energy system-wide energy and emissions impacts of vastly different, yet entirely plausible, oil price paths. In this context, it is worth noting that our analysis does not focus on short-term oil price trends, which tend to be dominated by investment cycles and strategic behavior of important market actors, but rather on longer-term oil price dynamics, which are likely to be driven more by the fundamental development of production costs (e.g., as in the case with shale gas)[16,17]. Our low oil price scenario is thus consistent with a future of strong technological change in unconventional oil extraction, leading to lower costs of production, while the high price scenario represents a future with less innovation in oil extraction. (Alternately, a future with severely muted cumulative oil demand could also result in sustained low oil prices, since the unconventional supplies would barely be tapped, if at all. We do not model such a future.)

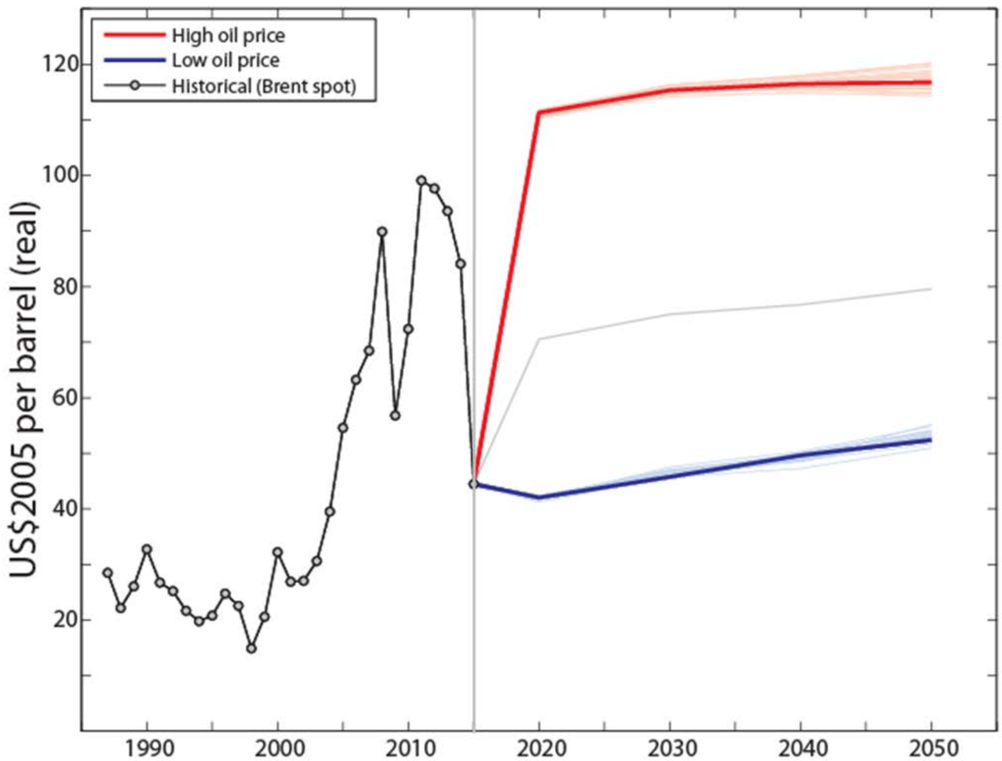

Figure 1. Oil price levels targeted in the two diverging cases. Dark red/blue lines represent the central case values; light red/blue lines derive from the numerous climate policy, energy resource, and supply and demand technology sensitivity cases. The grey line presents an intermediate oil price case; while not discussed in this paper, this is the model's default price projection and is meant to portray a continuation of the multi-year average trend between 2006 and 2012. The prices reproduced here exclude any incremental fuel costs imposed by carbon pricing. Historical data from U.S. EIA[14].

Historically, markets throughout the world have witnessed a strong relationship between oil and gas prices[18,19]; yet, there are signs that this relationship is evolving, at least in certain markets (e.g., in the United States)[1,20-23]. The emergence of new market dynamics – related to, for example, hydraulic fracturing for gas production or the international trade of liquefied natural gas (LNG) – is a key uncertainty for the future. Hence, in our set of reference case scenarios (both baseline and climate policy), we assumed that natural gas prices continue to rise and fall in concert with oil prices (in relative terms) across all markets, except in the US where we assume only weak correlation. Then, in sensitivity analyses attempting to capture a wholly new market paradigm, we explored scenarios where oil and gas prices fully decouple worldwide.

In addition to the unknown future linkage between oil and gas prices, the precise energy and emissions impacts of oil prices may be expected to depend on future uncertainties and assumptions regarding, among other things: (i) the presence and magnitude of carbon pricing; (ii) the availability and potential of sustainable biomass for energy purposes; (iii) the costs and potential of producing biofuels and fossil synfuels (coal- and gas-to-liquids); and (iv) the costs and availabilities of alternative fuel vehicle technologies (electric, hydrogen, and natural gas). Sensitivity analyses focusing on these numerous climate policy, energy resource, and supply and demand technology uncertainties were run with MESSAGE (see Table 1 and Methods and refs. [24-26] for background), in order to quantitatively assess the importance of individual factors thought to influence the ultimate impacts of oil prices on the global energy system.

Table 1. Summary listing of sensitivity cases.

Sensitivity Case	*Description, Main Assumptions, and Differences from Central Case*
(1) Potential supplies of sustainable biomass for energy purposes	Assumes that global primary bio-energy supply (excluding traditional biomass) is limited to 100 EJ/yr at all points in time (see refs. [24,25] for further details); this is consistent with the lower end of sustainable bioenergy potential assessed by the IPCC[26]. Unique constraints are imposed for each region in MESSAGE.
(2) Biofuels production costs and availability/scalability	Assumes that the fully learned-out investment and operations and maintenance (O&M) costs of the production technologies are 33% lower/higher than in the central case (e.g., 873-1316 US$2005/kW, depending on technology, in the central case). In combination, more optimistic/pessimistic assumptions for the overall market potential of these technologies are made by assuming maximum allowable (annual) diffusion rates that are two %-points higher/lower than in the central case.
(3) Fossil synfuels production costs and availability/scalability	Assumes that the fully learned-out investment and O&M costs of the production technologies are 33% lower/higher than in the central case (e.g., 473-1252 US$2005/kW, depending on technology, in the central case). In combination, more optimistic/pessimistic assumptions for the overall market potential of these technologies are made by assuming maximum allowable (annual) diffusion rates that are two %-points higher/lower than in the central case.
(4) Biofuels & fossil synfuels production costs and availability/scalability	Combination of sensitivity cases #2 and 3.
(5) Coupling between oil and natural gas prices	Assumes that oil and natural gas prices fully decouple worldwide in the future (e.g., a 100% change in the oil price results in a 0% change in the gas price, relative to default/intermediate levels). The central case assumption is that gas prices continue to rise and fall in concert with oil prices (100%-to-100%) across all markets, except in the US where only weak correlation is assumed (100%-to-50%).
(6) Electric vehicle costs and availability/scalability	Optimistic case assumes that 'behavioral barriers' to advanced vehicle adoption are largely overcome for the bulk of the population (with respect to, for instance, range anxiety, extent of refueling/recharging infrastructure, and risk aversion). For light-duty vehicles in particular, this amounts to an effective cost reduction of US$3,000-15,000 (depending on the year between 2030 and 2050) off the central case vehicle purchase price. We recognize that modeling 'behavioral barriers' as extra cost terms has important indirect resource implications in a general equilibrium context; yet, the aggregate sum of these costs is itself so small (relative to aggregate energy/technology-related costs) as to have no material bearing on the general equilibrium solution. In addition, assumed upper limits on the maximum contribution of electricity to total transport service demands were relaxed: from 35-50% (depending on the region; in any year to 2100) to 70% (across all regions). Pessimistic case assumes vehicle costs that are higher and maximum contributions that are lower than in the central case (e.g., US$6,000-8,000 cost increase for light-duty vehicles, and a decrease in the total transport contribution from electricity of 35-50% down to 25%). For more details

	about the modeling of the transport sector in MESSAGE, see ref. [25].
(7) Natural gas vehicle costs and availability/scalability	Optimistic case assumes an effective cost reduction for light-duty natural gas vehicles of US$3,500-16,500 and an increase in the total transport contribution of natural gas from 10-30% to 70%. No pessimistic case was run because the technology does not experience any significant deployment by 2050 in the corresponding central case. See ref. [25] for more information.
(8) Hydrogen vehicle costs and availability/scalability	Optimistic case assumes an effective cost reduction for light-duty hydrogen vehicles of US$9,000-63,000 and an increase in the total transport contribution of hydrogen from 60% to 70%. No pessimistic case was run because the technology does not experience any significant deployment by 2050 in the corresponding central case. See ref. [25] for more information.
Climate policy	Assumes varying levels of a globally-harmonized carbon price trajectory, from 0 to 61 US$/t$CO_2$eq in 2030 (central case: 13.5 US$/t$CO_2$eq). Price comes into effect in 2020 and grows with an interest rate of 5%/yr throughout the century. Such carbon pricing in the MESSAGE framework leads to temperatures of between 4.1-4.2 °C and 2.0-2.1 °C (median likelihood) above pre-industrial levels. For reasons of simplicity and consistency (in light of the oil price focus of this paper), we impose carbon pricing via taxes rather than via carbon caps (wherein the carbon price would result from the model endogenously). In the MESSAGE framework, these two carbon pricing mechanisms are synonymous.

One set of sensitivities assumes varying levels of stringency for global climate policy – from ‘baselines’ only considering existing policies to more transformative futures where average global temperatures peak at around 2 °C above pre-industrial levels (see Table 1). In this context, we note that the mitigation scenario focused upon in this paper is referred to as our ‘reference climate policy’ storyline. The moderate carbon pricing assumed in this scenario leads to roughly 2.6-2.7 °C warming (median likelihood) above pre-industrial levels by 2100 (with temperatures peaking soon afterwards). The financial signals from carbon pricing and oil pricing impose similar pressure in these scenarios, with neither overly governing the future that unfolds.

Energy and emission impacts of alternative oil price futures

Our scenario exercise leads to several insights with implications for energy-climate policy, technology, and markets. Firstly, sustained low or high oil prices could have a major impact on the global energy mix (i.e., ‘substitution effects’) between now and 2050 (see Figure 2, focusing on the results with our central case assumptions, i.e., ignoring the uncertainty ranges for the moment). As expected, low oil prices lead to considerably greater (cumulative) use of oil in both the baseline and climate policy scenarios. Similarly, if natural gas prices remain coupled to oil prices across all regional markets, then the future might also see a similar expansion of gas use in a low oil price world. For both resources, utilization of unconventionals[16,27] is greater in the low oil price scenario. This dynamic is consistent with a future of strong technological change (over the long term) in unconventional oil extraction, leading to lower costs of production, while the high price scenario represents a future with less innovation in oil extraction. Meanwhile, coal and low-carbon energy (namely biomass) see greater deployment under high oil (and gas) prices. This is due to biomass- and coal-based energy carriers (liquid fuels, gases, electricity) both reaching cost-competitiveness with oil- and gas-derived energy forms. Synfuels production (without carbon capture and storage in the baseline; with it in the climate policy scenario) is, in fact, responsible for a considerable amount of the increased coal consumption seen in the high oil/gas price case. Electric and biofuel vehicles also make much greater inroads by mid-century in the high oil price case; natural gas vehicles, in contrast, fail to do the same. Perhaps surprisingly, according to our analysis, the other low-carbon primary resource options (solar, wind, hydro, geothermal, and nuclear) experience only a slight uptick in the high oil/gas price case, principally because the substitution possibilities for nuclear and non-biomass renewables are largely restricted to electricity generation, and in this sector inexpensive coal represents a more cost-effective option (so long as carbon pricing remains relatively moderate up to 2050). Finally, we note that the fuel substitution dynamics discussed here are also found under various other levels of climate policy stringency (i.e., comparing the low and high oil price cases for the same carbon price; see Supplementary Tables 1 and 2 and Supplementary Figure 1 for details).

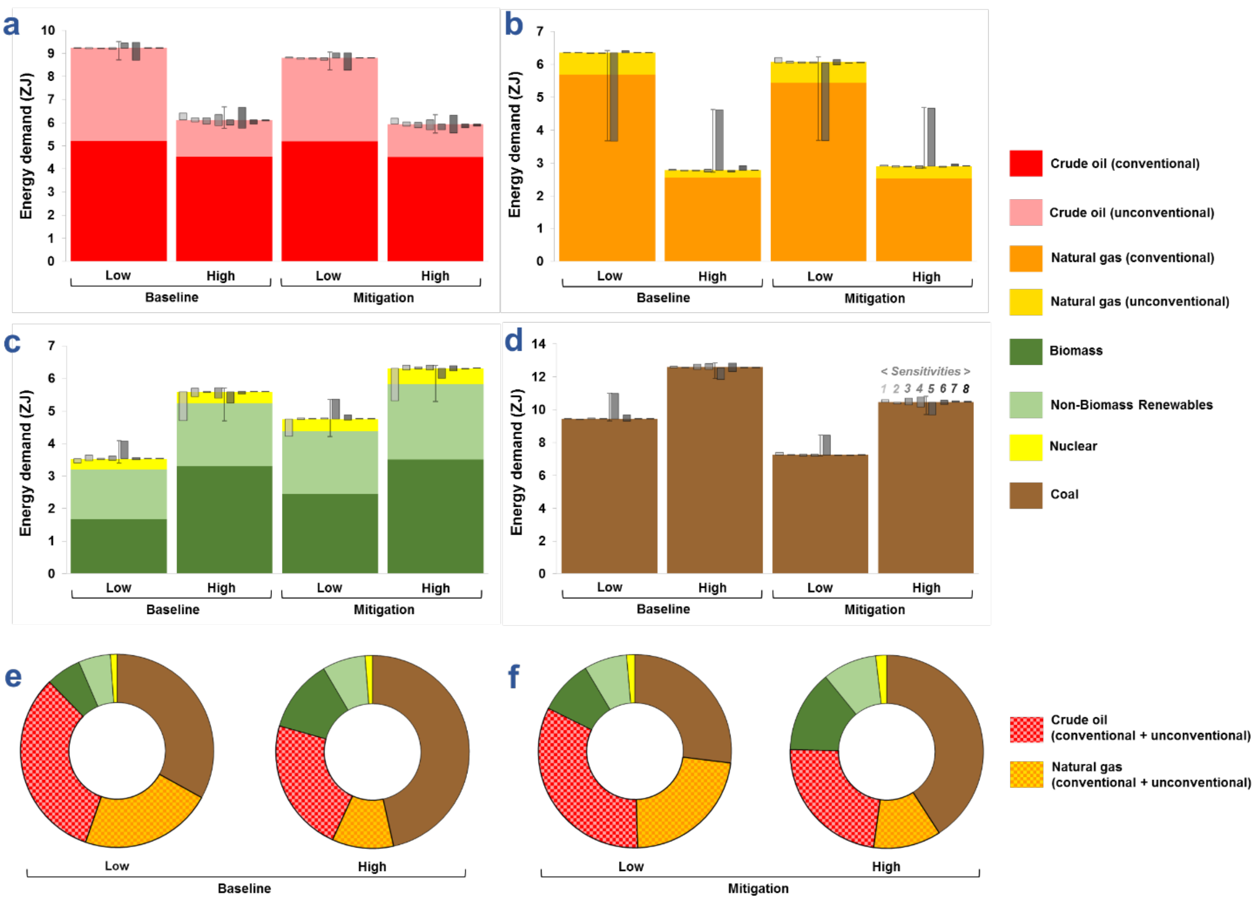

Figure 2. Cumulative energy demand from 2010 to 2050 by primary resource under low or high oil prices. (a-d) Energy demand in the case of no climate policy ('Baseline') and the reference climate policy ('Mitigation') scenarios under low or high oil prices for (a) crude oil, (b) natural gas, (c) low-carbon resources (biomass, non-biomass renewables, and nuclear), and (d) coal. In a,b, crude oil and natural gas are sub-divided into conventional and unconventional resources (e.g., oil sands, shale oil and gas, and tight gas), following the definitions of refs. [16,27]. Uncertainty ranges are given by the small grey bars of varying shades overlaid along the tops of the main bars. These reflect minimum/maximum values obtained for individual scenarios within the relevant set of sensitivity cases, numbered according to the definitions in Table 1. Error bars positioned at the top of each main bar reflect the full range of uncertainty across the entire suite of sensitivity cases. Note the different y-axis scales of the charts. (e,f) Percentage shares of cumulative energy demand by resource type for (e) no climate policy ('Baseline') and (f) the reference climate policy ('Mitigation') scenarios. Conventional and unconventional oil/gas are combined here. The colors are common to

all panels, denoted by the key. Note that in the mitigation cases a minority share of the coal- and gas-based energy is equipped with carbon capture and storage (coal: 7-12%, gas: <1%). Supplementary Tables 1 and 3 contain the data for the charts. One zettajoule (ZJ) is equal to one sextillion (10^{21}) joules; for reference, annual global primary energy production in 2010 was approximately 0.5 ZJ.

These findings regarding fuel substitution dynamics under either low or high oil prices vary across our different supply- and demand-side sensitivity cases. One sees this by noting the uncertainty ranges overlaid along the tops of the bars in Figure 2 (see Supplementary Tables 1 to 4 for numerical details). Eight separate sensitivities are presented (see Table 1, excluding the climate policy sensitivities); of these, the one leading to the largest variation in our results (i.e., for the different fuels in the various scenarios) is the uncertainty surrounding the future correlation between oil and gas prices (#5). If prices do manage to decouple globally, then natural gas deployment stands to gain considerably from sustained high oil prices (because gas would remain moderately priced, midway between the low and high case levels), whereas the opposite would be true in a low oil price world. While these dynamics may be expected in the directional sense, the magnitude of the swing is arguably quite dramatic. We note, for instance, that in both baseline and mitigation scenarios total natural gas consumption under high oil prices becomes significantly greater (~1 ZJ cumulative to 2050) than under low prices – a complete reversal from the scenarios with our central case assumptions. This is largely explained by gas replacing coal, non-biomass renewables, and nuclear for power generation, along with some substitution of gas for oil and coal in industry and for oil in buildings applications (either for heating or as a chemical feedstock). Another important sensitivity relates to the availability and potential of sustainable biomass for energy purposes (#1). If global supplies are constrained to just 100 EJ/yr at all points in time (i.e., at the lower end of the potential assessed by the IPCC[26]; in the climate policy scenarios this sees all regions running up against their bioenergy limits from 2020 onward), then cumulative biofuels demand could be as much as ~1 ZJ lower, with oil- and coal-based liquid fuels filling the gap. In contrast, uncertainties surrounding the future costs and availability/scalability of biofuels and fossil synfuels production (#2, 3, 4) are found to affect the energy mix in a relatively minor way across the various scenarios. Similar observations are made when assessing the demand-side sensitivity cases focusing on the future costs and availability/scalability of advanced transport technologies (#6, 7, 8). The one exception relates to electric vehicles: cumulative oil demand swings through a range approaching ~1 ZJ depending on the future competitiveness of this nascent class of technologies.

Our second key insight is that, depending on how the fuel substitution dynamics play out, the potential impacts of sustained low or high oil prices on CO_2 emissions could be significant. The lower the oil price, the stronger the carbon price signal that is needed to motivate a given level of CO_2 abatement; or put another way, for the same carbon price schedule, less abatement is achieved under lower oil prices. In our reference scenarios (either baseline or climate policy), future differences in global annual CO_2 emissions (from fossil fuels and industrial processes) between the two oil price cases are 3.5 to 4 $GtCO_2$/yr in 2030 and 6 to 7 $GtCO_2$/yr in 2050 (see Figure 3). For the latter year, this represents about 10% of emissions in the baseline scenarios and 20% in the climate policy scenarios. From a cumulative CO_2 perspective (2010-2050), emissions in the low oil price cases are nearly 140 $GtCO_2$ higher – approximately three to four years' worth of global emissions at current rates[28], or roughly 15% of the 2010-2050 budget for staying below the 2 °C target, according to the IPCC[29]. To put these numbers further into context, we note that recent analyses have estimated the global greenhouse gas (GHG) emission reductions resulting from countries' submitted (as of early-October 2015) Intended Nationally Determined Contributions (INDCs) to be 3.6 $GtCO_2eq/yr$ in 2030 (range: 0 to 7.5 $GtCO_2eq/yr$), relative to the levels expected under pre-INDC policies[30]. Viewed from these different perspectives, the emission differences brought about by vastly diverging oil price futures are certainly non-trivial; on the other hand, they are quite a bit smaller than the CO_2 reductions needed to safely achieve the 2 °C target[30-32]. What all of this suggests is that global mitigation efforts would be somewhat hampered by sustained low oil prices and somewhat boosted by sustained high prices.

That the *net* CO_2 emissions differences between our reference low and high oil price cases are not larger (or smaller) is primarily due to the parallel responses of coal and biomass (see Figure 2). Coal is relatively more carbon-intensive than biomass; hence, a simultaneous increase or decrease in the use of both fuels leads to a partial canceling out of the emissions benefits/consequences of one or the other. In addition to these countervailing fuel-emission dynamics, some of the difference in CO_2 between the low and high oil price cases is simply due to greater or lesser energy-service demands, respectively, (i.e., price-induced demand responses) in countries' end-use sectors: industry, transport, and buildings (further details can be found in Supplementary Tables 1 to 4 and Supplementary Figure 2; see refs. [33,34] for similar discussions). More specifically, our scenario analysis indicates that energy efficiency and conservation efforts are likely to suffer if oil prices remain low for an extended period of time, thereby putting further upward pressure on emissions (see also refs. [8,9]).

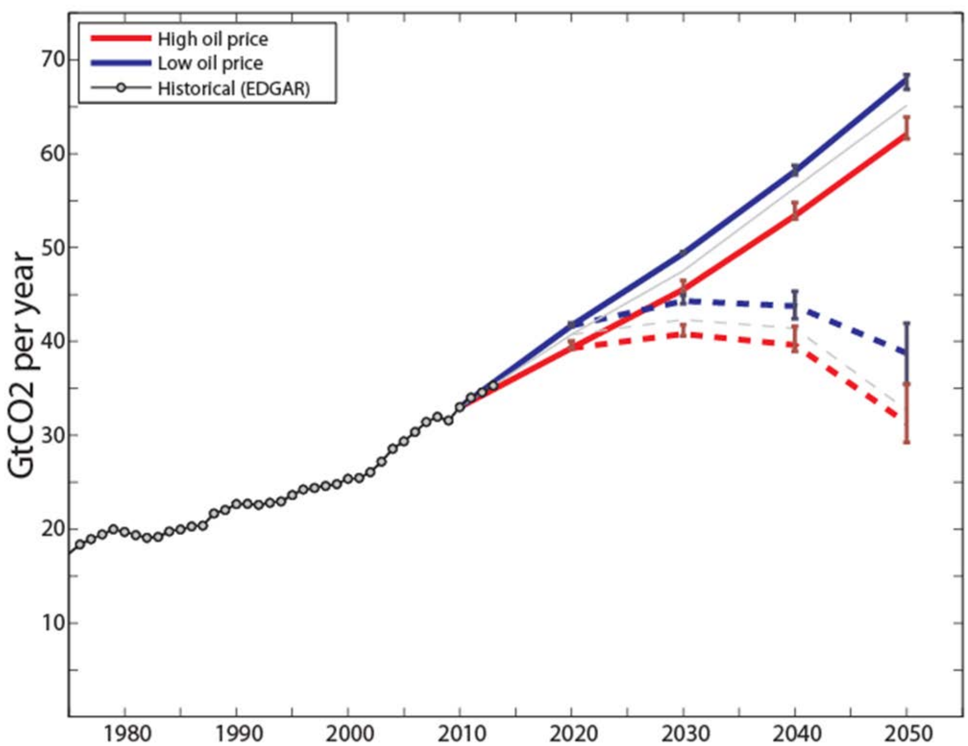

Figure 3. Fossil fuel and industrial process CO_2 emissions under low or high oil prices. No climate policy baseline: solid lines. Reference climate policy scenario: dashed lines. These are the same scenarios as in Figure 2. Uncertainty ranges reflect minimum/maximum annual emissions levels obtained for individual scenarios within the relevant set of sensitivity cases. Thin solid and dashed grey lines present emissions for an intermediate oil price case (see

Supplementary Table 5 for more information about this case). One gigatonne (Gt) is equal to one billion (10^9) metric tonnes. Historical data from ref. [28].

Sensitivity analyses focusing on the previously described uncertainties indicate that the CO_2 emissions impacts of oil prices may vary, with the spreads across the different cases being marginally greater in the reference climate policy scenarios than in the baseline scenarios (i.e., 13.5 and 0 US$/t$CO_2$eq carbon price in 2030, respectively; see Figure 3 uncertainty ranges, as well as Supplementary Tables 1 and 2, for cumulative values). Emissions differences are larger, for example, in both the optimistic biofuels production and pessimistic fossil synfuels production sensitivity cases, relative to the corresponding scenarios with central case assumptions: cumulative CO_2 under low oil prices is >140 GtCO_2 larger than under high prices. This is intuitive, considering that the former makes less carbon-intensive biomass more competitive while the latter makes more carbon-intensive coal less competitive. Similar observations and reasoning apply to the demand-side sensitivity cases making more optimistic assumptions for natural gas and hydrogen vehicles, as these back out oil- and coal-based liquid fuels in transport. In the opposite direction, the two sensitivity cases leading to smaller emissions differences (as low as 112 GtCO_2) are those related to limited biomass availability and oil-to-gas price coupling. Across the full suite of uncertainties, the difference in cumulative CO_2 between the low oil price sensitivity with minimum (maximum) emissions and the high oil price sensitivity with maximum (minimum) emissions is 97 (158) GtCO_2 in the baseline and 55 (194) GtCO_2 under climate policy (see Supplementary Tables 1 to 4). In other words, sustained low oil prices could lead to greater cumulative emissions that are as little as 5% or as much as 20% of the 2010-2050 budget for staying below the 2 °C target. Moreover, we note that, depending on the carbon price schedule, the emissions difference between low and high oil prices ranges from 110 to 139 GtCO_2. (Our most stringent climate policy scenario, i.e., with the highest carbon prices we tested, 61 US$/t$CO_2$eq in 2030, sees global temperatures peaking at slightly above 2 °C toward the end of the century; see Supplementary Figures 3 and 4 for details.)

The final insight stemming from our analysis is that if the stringency of global climate policy remains moderate over the next several decades to 2050, fluctuations in future oil prices could be at least as big a swing factor for crude oil, natural gas, coal, and low-carbon energy demand – if not bigger – than climate policy itself (Figure 2). For oil and gas in particular, we find that the quantities of these resources left in the ground (i.e., unburned[35]) by mid-century could be driven more by their own base prices (i.e., excluding any carbon price add-on) than by mitigation efforts. In contrast, climate policy would become the more dominant driver of energy system change if that policy would be quite stringent (i.e., of the type necessary for holding global temperature rise to around 2 °C). By our estimates with MESSAGE, this would be consistent with carbon prices in 2030 of 40 US$/t$CO_2$eq or greater. (Supplementary Tables 1 and 2 and Supplementary Figure 1 present energy mix results across a range of carbon price cases.) To be sure, we do not mean to suggest that carbon pricing at less substantial levels is unimportant for mitigating CO_2; indeed, our analysis shows that it will be critical, given that such policy instruments specifically target carbon-intensive fossil resources and can thus drive declines in CO_2. What our analysis instead highlights is that an extended period of either low or high oil prices would impact both fossil *and* non-fossil resources at the same time and in different ways; and this could have mixed effects on CO_2.

Conclusions

In summary, by employing the MESSAGE integrated assessment model, this study finds that sustained low or high oil prices could have a major impact on the global energy system over the next several decades; and depending on how the fuel substitution dynamics play out, the carbon dioxide consequences could be significant (e.g., between 5% and 20% of the budget for staying below the internationally-agreed 2 °C target). The variance in the impacts depends on a suite of critical uncertainties, chief among them the future coupling between oil and gas prices going forward.

Though not entirely comparable, a recent analysis by the IEA[1] looked at diverging oil price futures where prices slowly return to either high (128 US$/bbl) or mid (85 US$/bbl) levels by 2040. That analysis arrives at findings similar, in the directional sense, as we do: lower oil prices lead to greater cumulative oil and gas demand and lesser renewables and coal demand. In terms of magnitudes, however, the energy demand shifts we estimate (moving from high to low prices) are substantially larger (by one to two orders of magnitude) for each of the various energy sources: from +1.2 to +2.0 ZJ for oil, -0.6 to +2.3 ZJ for gas, -0.4 to -1.9 ZJ for coal, and -0.1 to -1.2 ZJ for renewables and nuclear (to 2040; values spanning all sensitivity cases), compared to +0.13 ZJ for oil, +0.01 ZJ for gas, -0.10 ZJ for coal, and -0.03 ZJ for biomass and non-hydro renewables according to the IEA's assessment (approximate calculations based on numbers shown in Table 4.1 of ref. [1]). Such trivial shifts in the energy mix in the latter likely explain why cumulative CO_2 emissions are estimated to be a mere 3 $GtCO_2$ greater in the IEA's mid oil price case, whereas we calculate the increase to be in the range of 50 to 98 $GtCO_2$ (to 2040). Inter-study discrepancies so immense point to deep uncertainties in how critical factors will drive energy system development, and by extension climate change mitigation, over the twenty-first century.

A caveat to the analysis described here is that a single model was employed to answer the questions posed and, thus, the results are conditional on the chosen framework. While previous work[36] has analyzed the long-term fossil resource dynamics of baseline and climate policy scenarios within a multi-model comparison context, no such comparisons have yet been carried out on the topic of oil prices, at least not as framed in this paper. Such an exercise could certainly be fruitful for the global modeling community, as it would eliminate yet another source of uncertainty on top of the numerous parametric sensitivity analyses that we conduct (i.e., the structural assumptions of models). Another important caveat to our analysis is that it only considers sustained low or high oil prices, whereas the combined dynamics of oil demand and oil field exploration and development will likely ensure that future oil prices are more volatile than the intentionally stylized paths assumed here. Future work might therefore consider studying, for example, the energy and carbon 'lock-in' effects of oil prices that remain low for a time but then rise to much higher levels afterwards (i.e., resource/technology/policy decisions made myopically; see ref. [37]). Finally, the topic of fossil fuel subsidies represents an area the global modeling community could continue to explore going forward: how do subsidies distort markets, and what might be the impacts of reforming them in various countries over the coming years?

Methods

Overview of the integrated modeling framework

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) integrated assessment framework is comprised of several inter-linked models. (Version 'V.5a' of MESSAGE was used for this paper.) At its core is a global energy-economic model based on a linear programming optimization (cost-minimization) approach which is used for medium-to long-term energy system planning and policy analysis[12,13]. For each of its eleven regions, the model provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy and their respective prices. At the primary level in particular, regionally-specific resource supply curves and extraction technologies (for crude oil, natural gas, coal, uranium, biomass, and other renewables) are specified as input assumptions (the oil supply curves vary by oil price case; see Supplementary Methods). This leads to an endogenous calculation of resource prices, which then contributes to the endogenous calculation of other commodity prices (secondary, final, and useful levels), considering costs for energy conversion and transport/distribution, as well as energy subsidies, taxes, and other price mark-ups.

For the estimation of price-induced changes of energy demand, iterations between MESSAGE and the macro-economic model MACRO are relied upon.[38] In MACRO, capital stock, available labor, and energy inputs determine the total output of the economy according to a nested constant elasticity of substitution (CES) production function. Through the linkage to MESSAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion, taking into account price-induced changes of both. Six different end-use demand categories are represented in MACRO: electric and thermal heat demands in the industrial and residential/commercial sectors (1-4), non-energy feedstock demands for industrial applications (5), and mobility demands in the transportation sector (6). Prices are calculated uniquely for each of these six demands, and therefore the macro-economic responses seen in the different sectors capture both technological and behavioral measures in each sector uniquely (at a high level of aggregation). MACRO is run for all eleven MESSAGE regions simultaneously.

MESSAGE is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6.8 (ref. [39]) for calculating climatic indicators such as atmospheric gas concentrations, radiative forcing, and annual-mean global surface air temperature. Much more detailed information about the MESSAGE modeling framework can be found in the Supplementary Methods and in refs. [12,13]. The following paragraphs focus on the innovative features that were implemented in MESSAGE in order to undertake the analysis described in the current paper.

Constructing the low and high oil price cases

Reproducing real-world price behavior in global IAMs has historically presented a challenge for modelers, and earlier studies have shown that oil and gas prices can diverge widely between frameworks, even in the base year[36]. IAMs have rather focused their attention on relative price differences between fuels. However, for undertaking the analysis with MESSAGE described in this paper, it was important for the model to represent oil and gas prices as precisely as possible. Hence, a novel methodological development enabling our analysis is that the endogenously calculated energy prices (both primary and final) in MESSAGE were adjusted so that they reproduce observed prices (for all regions, energy sectors and fuels). Toward this goal, an extensive data set of historical prices, subsidies and taxes was compiled from a number of sources (see refs. [40,41] for details). In fitting this data into MESSAGE, we assumed for both crude oil and coal that there is a single global price, since these fuels are globally traded. For natural gas, three separate regional market prices were used as benchmarks for the different MESSAGE regions, thereby reflecting regionally fragmented markets. Wherever possible, prices in the data set represent average prices from 2006 to 2010, in all cases converted to US$2005/GJ. The strategy for harmonizing the MESSAGE prices and the historical prices relied on the use of "price adjustment factors", which were applied to fuels at both the resource extraction and end-use levels. A hypothetical example illustrates how this works. If the model previously calculated the price of a given fuel in a particular sector and region to be 8 US$/GJ (based on the costs of resource extraction, conversion and distribution activities), but we know the price to be 12 US$/GJ from the historical data set, then a price adjustment factor of +4 US$/GJ (= 12 - 8 US$/GJ) was applied in order to increase the endogenous MESSAGE price to the observed price. At the resource extraction (primary energy) level, this translates into a shifting of the crude oil and natural gas supply curves in the vertical (price) dimension. The fuel/region/sector-specific price adjustment factors estimated for the base year were then held constant – in a given oil price case – throughout the time horizon of the model. The adjustment factors can be interpreted in the following way: they capture all components embedded in the price of fuels beyond their technology-related costs (i.e., things that models like MESSAGE are well-suited to represent, such as resource extraction, conversion and transportation costs). The factors explicitly represent both energy subsidies and taxes; residual terms then cover additional components such as producer rents/profits and speculation, among other things.

Alternative oil price cases were created by lowering or raising the price adjustment factors on oil until the desired price level was reached in 2020 (~40 US$/bbl in the low case, ~110 US$/bbl in the high case). Endogenously determined price dynamics then take over in the years after 2020, so that prices rise gradually in line with more costly grades of oil being consumed. The same is true of natural gas, depending on whether or not its prices were assumed to be coupled to oil; if not coupled, then gas prices remain at a moderate level in between the low/high extremes. In addition, we assumed that year-2020 subsidy rates for oil and gas (on both the supply and demand sides) scale proportionately with their respective 2020 prices; in other words, a given %-change in the price corresponds to a given %-change in the subsidy rates. This scaling algorithm is intended to reflect the dynamics of real-world subsidy schemes, which tend to fluctuate up and down with energy prices (see ref. [1]). Once the subsidy rate is set, it is held constant throughout the time horizon of the model.

Modeling the link between crude oil and natural gas prices

In the past, oil and gas prices tended to be correlated because (i) crude oil (and refined oil products) and natural gas were competitive substitutes in several energy and industrial sectors, (ii) the two resources were often produced using similar technologies by firms possessing similar expertise, and/or (iii) many gas supply contracts (particularly for liquefied natural gas, LNG) were indexed on oil prices.[42] So when oil prices rose (or declined), gas prices tended to as well, even if their absolute price levels differed considerably. The past several years have shown that these relationships could be undergoing a transition, however. In the United States, for example, oil and gas prices have recently decoupled, owing, at least partly, to hydraulic fracturing techniques for gas production[22]. Price correlation meanwhile remains strong in most of Europe and elsewhere[21,23]; though, this too could change over time if the fragmented gas markets of today become more globalized (with LNG being shipped over long distances, as is currently the case with crude oil). The emergence of these new market dynamics is a key uncertainty for the future – hence the sensitivity cases we run for the future coupling between oil and gas prices. In all instances, consistent with past observations[41], we assumed that subsidy rates for oil and gas (on both the energy supply and demand sides) scale proportionately with their respective prices.

Developing climate policy scenarios for the analysis

Climate policy, or 'mitigation', scenarios were run by imposing a globally-harmonized carbon price that begins in 2020 and grows with an interest rate of 5%/yr until the end of the century. ('Mitigation' meaning that CO_2 emissions are reduced below those of the no climate policy baseline.) For instance, the 'reference climate policy' scenario focused upon in this paper assumes a carbon price that begins in 2020 at 8.3 US$/t$CO_2$eq and grows with an interest rate of 5%/yr, reaching 13.5 US$/t$CO_2$eq in 2030 and 36 US$/tCO_2eq in 2050, before continuing into the hundreds of dollars later in the century. Such moderate carbon pricing in the MESSAGE framework leads to roughly 2.6-2.7 °C warming (median likelihood) above pre-industrial levels by 2100 (with temperatures peaking soon afterwards) and atmospheric GHG concentrations of approximately 615-635 ppm CO_2eq in the same year. Results for more stringent climate policy scenarios (i.e., with elevated carbon price schedules; some that come closer to achieving the 2 °C target) are presented in Supplementary Tables 1 and 2 and Supplementary Figures 1, 3, and 4.

Selecting the sensitivity cases to run

The sensitivity cases run for this study are summarized succinctly in Table 1. We of course recognize that, if not for computational constraints, an essentially limitless number of parametric assumptions could have been tested using our modeling framework. The subset of factors focused upon here was selected after careful consideration of the fuel substitution possibilities (for oil and gas) present in the transport, industry, buildings and power sectors.

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Author Contributions

DM, JJ, VK and KR designed the research. JJ contributed data for the modeling. DM and VK implemented the modeling. MF and MB provided feedback on the scenarios, in particular assisting with the policy framing. All authors contributed to writing the manuscript.

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